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PLANETARY SPECTRA

V. G. Teyfel'

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PLANETARY SPECTRA

-USSR-

/Following is the translation of an article by V. G. Teyfel', Academy of Sciences, Kazakh SSR (Alma-Ata), in the Russian-language publication Priroda (Nature), No. 6, Moscow, June 1961, pages 39-45/

For the time being the investigations of the planets of our solar system are being made only from the earth. The principal methods for this study are visual, photographic and electronic-telescopic observations of the surfaces of planets, photometric measurements and measurement of the color of their disks and individual details, study of planetary spectra, determination of the temperatures of planets, and finally, the investigation of the radio emission of planets, which has been developing successfully in recent years.

Spectroscopic Investigations.

The study of the light reaching us from celestial bodies by use of prisms or diffraction gratings is of maximum value in studying bodies which emit light themselves: the sun, stars and nebulae. The study of stellar spectra makes it possible to obtain the characteristics of their temperature, dimensions, etc., and determine whether a star has an extended envelope, what the rate of expansion of this envelope is and what the chemical composition of the outer layers of the star is. In actuality, virtually all the basic data concerning stars is obtained using spectral analysis.

The possibilities of the spectroscopic method are considerably more modest with respect to the planets. There is no intrinsic radiation in the optical region of a planetary spectrum; we observe and can investigate only solar light reflected by the solid surface or atmospheric layers of the planet. The spectral properties of the planet are determined only by those changes which it introduces into the solar spectrum. The principal physical characteristics of the planets were determined without the assistance of spectral analysis. Nevertheless, the greater part of the most interesting discoveries in the area of planetary physics, especially in the last 10-20 years, has been the result of spectral observations.

Spectroscopic investigations of the planets have developed in three principal directions: study of their rotation on the basis of the Doppler shift /see note/ of lines in the spectra, photometric study of the continuous spectrum of planets and search for new lines and absorption bands and study of already known lines and bands.

/Note: The Doppler effect is a change in the frequency of radiation of the source perceived by the observer with the approach and withdrawal of this source./

We now will discuss in greater detail the results of such investigations.

Carbon Dioxide and Water Vapor in the Venusian Atmosphere
/Note: See Priroda (Nature), 1960, No. 10, pp. 10-11./

By the use of spectral analysis it is possible to determine the presence in atmospheres of the planets of those gases which in the investigated region of the spectrum give rise to sufficiently strong lines and absorption bands. It is true that considerable difficulties arise when we attempt to discover gases which are present in great quantity in the earth's atmosphere. Since for the time being astronomers are forced to make observations of all celestial bodies through the thickness of our atmosphere, the strong, so-called telluric absorption bands of the gases in the atmosphere, especially oxygen and water vapor, in fact screen the weaker lines and bands of these same gases in the atmospheres of other planets.

Therefore, until recently, it has not been possible to detect the lines of oxygen and water vapor in the spectra of Mars and Venus, the planets most similar to the earth. But the situation is different with respect to other regions of the spectrum, especially the infrared region. In 1932 the American astronomers W. Adams and T. Dunham discovered strong absorption bands in the spectrum of Venus; these were in the infrared region (wavelengths from 0.7 to 2.0 μ) or more. It was found that they belonged to carbon dioxide gas (Fig. 1).

A quantitative analysis of the intensity of the bands revealed that the CO_2 content in the Venusian atmosphere is approximately 100 times greater than in the earth's atmosphere. Later, in 1948, carbon dioxide was discovered by Kuiper in the Martian atmosphere in a quantity exceeding by a factor of 3 its content in the earth's atmosphere.

In order to attenuate the influence of the earth's atmosphere on the results of astrophysical observations, in recent years scientists have begun to send astronomical instruments aloft by balloons to heights greater than 15 km. Under these conditions the telluric lines in the spectra of celestial bodies are less intense. In 1959 M. Ross and C. Moore (United States), investigating the Venusian spectrum from an altitude of 27 km, discovered an enhancement of these lines of water vapor in comparison with the spectra of other celestial bodies. Such enhancement can be caused by the presence of water vapor lines in the Venusian spectrum. The investigators concluded that there is less water vapor in the upper layers of the Venusian atmosphere, lying above its cloud layer, than in the upper layers of the earth's atmosphere. If this is so, the quantity of water vapor in the lower layer of the Venusian atmosphere can be even greater than in the earth's atmosphere. The discovery of water vapor on Venus sheds light also on the nature of its clouds, concerning which a wide range of hypotheses has been developed, even a hypothesis that these clouds consist of solid particles of formaldehyde (CH_2O).

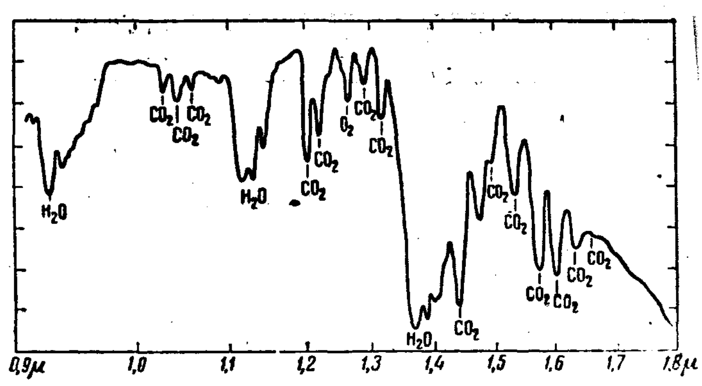

Fig. 1. Absorption bands of CO_2 and telluric bands of water and oxygen in the spectrum of Venus.

In 1953 N. A. Kozyrev found two absorption bands belonging to some unknown molecule in the violet part of the Venusian spectrum at wavelengths 4120 and 4372 A. Subsequent observations revealed that this molecule also is present in the earth's atmosphere.

Auroras on Venus.

Powerful fluxes of electrically charged particles -- corpuscles -- emitted by active regions on the sun encounter the planets along their path. The magnetic field of the earth deflects and captures the incident corpuscular stream, whose particles with great velocity penetrate the upper layers of the earth's atmosphere, causing luminescence of the rarified gases in these layers. This luminescence is observed in the high latitudes in the form of auroras and everywhere as a weak emission detected from the presence of bright lines in spectra of the night sky.

Surrounded by a not less dense atmosphere, Venus is situated almost 1½ times closer to the sun than the earth, and therefore is subject to a considerably stronger effect from solar radiation. It has been established from the deflections of corpuscular streams passing near Venus that it has a magnetic field and its strength is five times greater than the earth's magnetic field. Under such conditions the luminescence of the upper layers of its atmosphere should be many times stronger than the luminescence of the earth's atmosphere.

In 1953, N. A. Kozyrev, while photographing the spectra of the night side of Venus with the 50" reflector of the Crimean Astrophysical Observatory, discovered for the first time weak emission bands, noticeable on a spectrogram, at the limb of the night side of the planetary disk. He identified these emission bands with the bands of nitrogen emission observed in the spectra of terrestrial auroras.

Similar observations were made in 1958 by the astronomer Newkirk, who also discovered indications of emission in certain parts of the spectrum of the unilluminated part of Venus. A number of the emission bands which he noted coincided in position with those found by N. A. Kozyrev. The intensity of the radiation bands, according to the computations made by these investigators, is evidence that the luminescence of the Venusian night sky is more intense by a factor of 50-80 than the luminescence of the earth's night sky.

Is There Vegetation on Mars?

The results of spectral observations of dark regions on Mars have long been considered an argument against, rather than in support of the hypothesis that these regions are covered by vegetation, since the comparison of their spectra with the spectra of terrestrial plants revealed no similarity. In the case of terrestrial plants there is a characteristic presence of the absorption band of chlorophyll in the spectrum at wavelengths from 6000 to 7000 A and a sharp increase in brightness in the infrared part of the spectrum. However, in the spectra of Martian dark regions these effects are absent. However, in the studies made by G. A. Tikhov, head of the Astrobotany Section of the Academy of Sciences of the Kazakh SSR, and his colleagues it has been shown that under the arid climatic conditions of Mars plants can absorb infrared rays and the chlorophyll band broadens, becoming less noticeable. In actuality, similar phenomena are observed in the spectra of terrestrial plants under low-temperature conditions.

New data supporting the hypothesis of the existence of vegetation on Mars was obtained recently by observations in the far infrared region of the spectrum. In 1956 the American astronomer W. Sinton at Harvard Observatory studied the integrated light of Mars, and in 1958 with the more modern apparatus of the 200" reflector at the Mount Palomar Observatory he investigated the dark and light regions of Mars. In the spectra of the dark regions he found three absorption bands at wavelengths 3.43, 3.56 and 3.67 μ, absent in the spectra of bright regions and the sun (Fig. 2). The first two bands are seen clearly in spectra of lichens of the genus Physcia and the algae Cladophora, shown in the same figure. Sinton also demonstrated that the absorption bands of an organic molecule cannot appear in the Martian atmosphere. Thus, at present spectral observations indicate that there is vegetation in the dark regions of Mars.

Hydrogen and its Compounds in the Atmospheres of the Giant Planets.

The giant planets of the solar system -- Jupiter, Saturn, Uranus and Neptune -- have much in common with one another, not only with respect to size, but also in the chemical composition of their atmospheres. Their spectra have clearly defined absorption bands of methane (CH_4), which were observed by Huggins (United States), using a visual spectroscope in observing Uranus, at the early stages in such planetary observations. These bands are the strongest in the spectra of Uranus and Neptune (Fig. 3). The presence of methane bands in both the infrared and visible parts of the spectrum indicates a very high content of this gas in the atmospheres of the giant planets. In laboratory investigations it is customary to observe only the infrared absorption bands of methane, situated near the principal oscillation frequencies of the CH_4 molecule.

In the spectra of Jupiter and Saturn there are bands of still another hydrogen compound -- ammonia (NH_3); they are considerably weaker in the spectrum of Saturn than in the Jovian spectrum and disappear in the spectra of the more distant planets -- Uranus and Neptune.

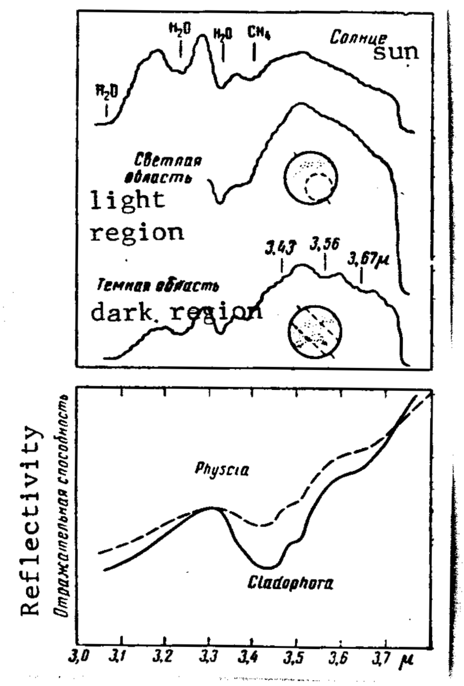

Fig. 2. Absorption bands of an organic molecule in the spectrum of lichens and algae. The dashed lines on the representations of Mars outline the investigated zones of the planet.

How can such a difference in the spectra be explained? It is found that the most important factor here is the lower temperature of the planets which are distant from the sun. Thus, whereas in the atmospheres of Jupiter and Saturn a certain quantity of ammonia can be in a gaseous state (this gas can be formed by the sublimation of ammonia crystals suspended in the atmosphere), in the atmospheres of Uranus and Neptune all the ammonia in a solid state settled onto the surface of the planet.

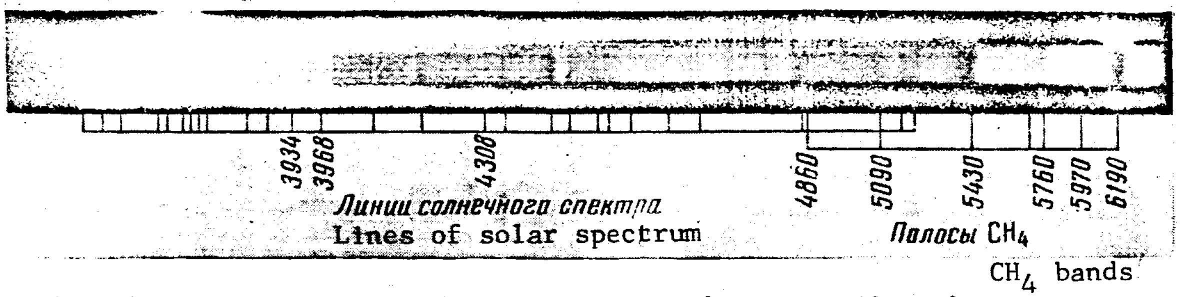

Fig. 3. Spectrogram of Uranus, obtained at the observatory of the Astrobotany Section, Academy of Sciences, Kazakh SSR.

Repeated investigations have been made of the methane bands in different parts of the Jovian disk. It can be assumed that with approach to the limb the intensity of the methane bands should increase, since the distance passed by the line of sight in the atmosphere increases toward the planetary limb. However, observations made by S. Hess (United States) and N. T. Bobrovnikov, D. I. Yeropkin and the author of this article show that there is no such increase. Hess and Squires have attempted to explain this phenomenon. Hess assumes that as a result of a decrease of the temperatures of the eastern and western limb of Jupiter in comparison with the center of the planet the cloud layer is higher at the limb than near the center. However, Squires pointed out that this hypothesis does not agree with the temperature regime of Jupiter and advanced a different hypothesis. He assumes that the cloud layer of Jupiter does not have an even upper boundary, but consists of cumulus clouds whose tops rise to several kilometers above the main cloud deck.

However, both these hypotheses assume that the absorption bands of methane arise during the passage of light through a purely gaseous layer. Theoretical computations reveal, however, that methane bands will be observed even in a case when methane is present only within the cloud layer and the intensity of the bands should decrease toward the limb. However, if a purely gaseous layer is situated over an even cloud layer, in the case of a particular thickness of the latter the increase of absorption within the layer toward the limb can compensate the decrease of intensity of the methane bands so that the total intensity of the bands will remain virtually unchanged.

The presence of a large quantity of hydrogen compounds in the atmospheres of the giant planets indicates indirectly that they contain free molecular hydrogen, which, however, was not discovered spectroscopically until recently. Careful investigations of the spectra of the giant planets led to the discovery by G. Kuiper (United States) of a weak washed-out band with a wavelength of 8270 A in the spectra of Uranus and Neptune. The American physicist-spectroscopist H. Hertzberg made laboratory investigations of the absorption spectrum of molecular hydrogen. In this study he investigated the spectrum of hydrogen which was under a pressure of 100 atmospheres in a tube with the equivalent length of an optical path 80 m in length /see note/. He discovered three washed-out bands, of which one was very close to that found by Kuiper. Although hydrogen in the spectra of the giant planets does not give rise to strong bands, from theoretical considerations it should play a predominant role in the atmospheres of these planets.

/Note: In this case the equivalent length of the optical path is equal to the path which a light ray would travel in the earth's atmosphere at normal pressure in order to experience the same absorption as in the above-mentioned experiment./

In 1957 a detailed investigation was made at the observatory on Mauna Loa in Hawaii to determine the structure of the methane and ammonia bands and strong absorption was discovered in the Jovian spectrum at wavelengths of less than 4200 A. These bands, in the opinion of the American researchers Kiss and Corlis who discovered them, are caused possibly by the presence of the N_2O_4 molecule in the Jovian atmosphere. But what is most important is that these investigators were able to detect a band of molecular hydrogen in the Jovian spectrum.

Meteoric Nature of the Rings of Saturn.

According to the well-known Doppler-Fizeau principle, whose experimental checking for light was accomplished by A.A. Belopol'skiy, in the spectrum of a moving light source all the lines are shifted toward the violet end if the source is moving toward the observer and toward the red end if the source is withdrawing from the observer. When the spectrograph slit is oriented along the equator of a rapidly moving planet all the lines in the spectrum will have an appreciable inclination, since one limb of the planet is approaching us and the other is withdrawing. The spectral lines are displaced proportional to the velocity of approach and withdrawal of each point of the planet's equator.

By means of this method A. A. Belopol'skiy and the American astronomer Keeler in 1895 demonstrated the meteoric structure of the ring around Saturn. If each of the systems of rings of Saturn was continuous, the outer edges of the ring would have a greater linear velocity than the inner rings. The inclination of the lines in the spectrum of the ring would coincide with the inclination of the lines of the planetary disk. But in actuality the opposite picture is observed -- the shift of the lines in the inner parts of the ring is greater than in the outer parts, which corresponds to a decrease in the linear velocity of rotation of the ring with increasing distance from the planet (Fig. 4). The latter fact indicates that the ring of Saturn cannot be continuous, but instead consists of a large number of individual particles, each of which follows its path around the planet in conformity to the laws of celestial bodies.

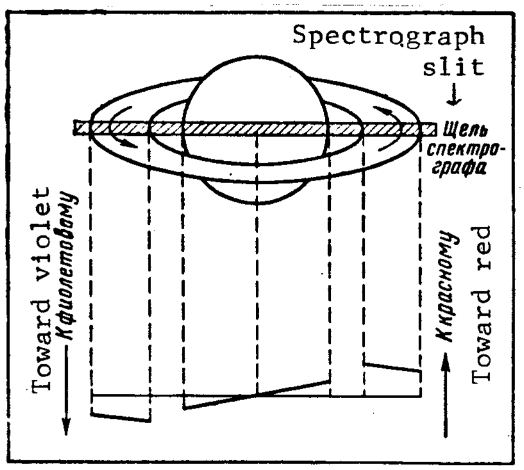

Fig. 4. Shift of lines in the spectrum of the disk and ring of Saturn. In the left part of the ring the lines are displaced toward the violet, and in the right part -- toward the red end of the spectrum. The maximum shift is observed near the inner parts of the ring.

Color of the Lunar Surface.

Among the varied investigations of the lunar surface the study of the color properties of its formations are of more than a little interest. On the basis of the changes introduced by parts of the lunar surface into the spectrum and brightness of the solar rays incident upon them it is possible to form an opinion concerning the properties of the rocks making up the lunar relief.

Color gradations on the moon are distinguished visually only with great difficulty, and then only by experienced observers. Instrumental determinations of the color of lunar details long yielded contradictory results. This led to a discussion over the years concerning the existence and magnitude of color differences on the lunar surface. The discussion of this problem is by no means scholastic, since the color properties of the lunar surface depend on the state of its outer layer, which continuously is subject to external influences: exposure to cosmic radiation and ultraviolet rays, bombardment by meteorites and micrometeorites. The lunar crust experiences considerable changes in the process of tectonic development. Consequently, by determining the degree of color differences on the lunar surface we can judge the petrographic state of lunar rocks and the state of the surface layer of the moon.

Colorimetric and spectrophotometric observations of the lunar surface are being made at the present time at a number of Soviet observatories: N. P. Barabashov, V. I. Yezerskiy and V. A. Fedorets at Khar'kov, V. V. Sharonov at Leningrad, A. N. Sergeyeva at Kiev, T. A. Polozhentseva at Pulkovo and the author at Alma-Ata. This work is leading to quite definite results: color differences actually exist on the moon, although incomparably smaller than the color differences of terrestrial rocks and meteorites. This can be seen, for example, from Fig. 5, which gives the spectral curves of the two lunar details differing most sharply in color and two stony meteorites. Spectrographic investigations make it possible to postulate that even lunar rocks not subjected to external influences are less varied in their spectral properties than terrestrial acidic rocks of the granite type and basic rocks of the basalt type.

Still another peculiarity is characteristic of the lunar surface -- its brighter details also are more reddish and there is a proportional relationship between their color and the relative brightness of the details. The entire moon is reddish as a whole in comparison with the sun, that is, a comparison of the spectral curves derived from moonlight and the sun reveals that the brightness in lunar spectra is increased with a transition from short to long waves.

The sun's rays are polarized upon reflection from the lunar surface. The maximum polarization is observed when the moon is in the first and last quarters. Spectral observations have made it possible to establish that the degree of polarization of lunar details changes somewhat with wavelength, increasing toward the blue end of the spectrum. This phenomenon is easily attributable to the "N. A. Umov effect" -- the dependence of the degree of polarization on the brightness of the surface scattering light at different wavelengths. In those rays which are absorbed more strongly by the surface, the degree of polarization of the light scattered by the surface will be maximum. However, the rays which are reflected more intensively by the surface (they determine its apparent color) will have a lesser degree of polarization. The lunar surface absorbs blue rays more strongly, as indicated by its reddish color, that is, it is in the blue rays that the degree of polarization of the sunlight reflected by the moon should be maximum. The spectral-polarization properties of lunar features can be different. For the time being their investigation is only beginning and this investigation undoubtedly will be useful for clarifying the composition of lunar rocks.

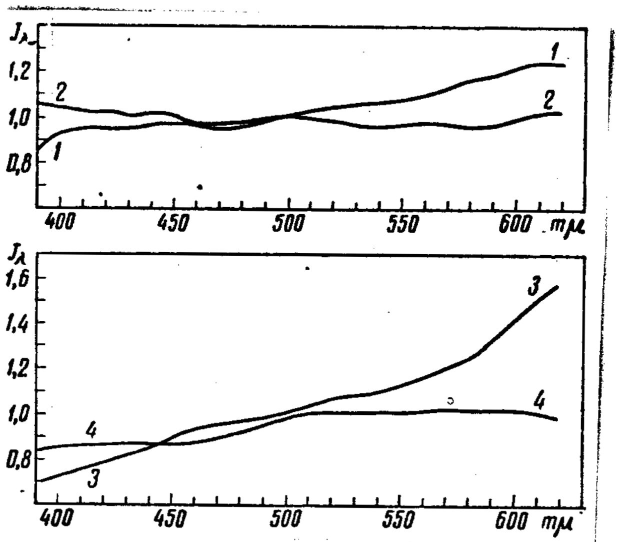

Fig. 5. Maximum differences in the spectral reflectivity of parts of the lunar surface (1 and 2) and stony meteorites (3 and 4).

Luminescence of the Lunar Surface.

At the time of lunar eclipses many observers have noted that individual details of the lunar surface plunged into the earth's shadow appear somewhat brighter than the surrounding background in comparison with the time before the eclipse. The Czech astronomer F. Link has attributed this phenomenon to the fact that certain parts of the moon become luminescent under the influence of solar ultraviolet radiation.

Once again, it was possible to use spectral observations, in this case to confirm the existence of luminescence of the lunar surface. N. A. Kozyrev in the USSR and J. Dubois in France have used the following method for this purpose. The spectrum of the moon, illuminated by the sun's rays, contains all the Fraunhofer lines of the solar spectrum. If there are bands of luminescence -- bands of luminescence of the lunar surface itself -- in any region of the spectrum, the profiles of the Fraunhofer lines in this region will be distorted somewhat and their depth will decrease.

The investigation in the spectra of a number of lunar details of the profiles of the strongest lines -- H and K -- belonging to the ionized calcium of the solar atmosphere, made it possible for N. A. Kozyrev to detect luminescence of the brightest object on the visible lunar surface -- the crater Aristarchus. Dubois, on the basis of the profiles of lines and the distribution of intensity in the continuous spectrum, found indications of luminescence bands for many craters and sectors of lunar plains. The brightness excess, caused by luminescence, according to Dubois attains 20%. By means of laboratory experiments he found that the detection of luminescence requires the presence in the outer layer of the lunar surface of only 1% of the luminescent matter. For the time being these data are of a preliminary character and require checking by further observations. With respect to Aristarchus crater, a whole series of peculiarities of that feature make it possible to assume that we observe matter in this crater which is appreciably different from the surrounding lunar surface. This is indicated by the great brightness of the crater, its luminescence and the author's recent discovery of a deviation from the ordinary dependence between color and brightness which is satisfied by all other parts in this region of the moon.

N. A. Kozyrev believes that the luminescence of lunar details can be caused not only and not so much by solar ultraviolet radiation as by solar corpuscular streams. In 1958 N. A. Kozyrev and V. M. Yezerskiy discovered by means of spectral observations that gases are emanating from the central part of the crater Alphonsus.

All these facts show that the moon is today an extensive field for spectral investigations.

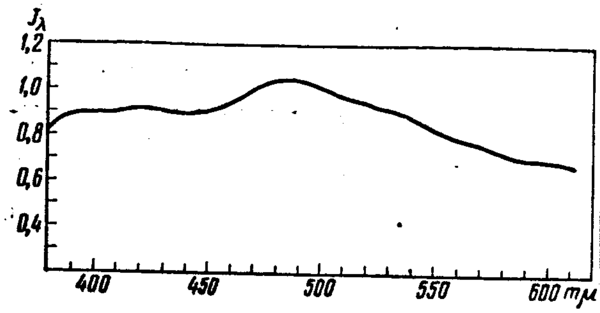

Fig. 6. Curve of the distribution of intensity in the spectrum of Vesta in relation to the spectrum of a star of a spectral class close to the sun.

Spectra of the Minor Planets.

The minor planets (asteroids) are among the bodies of the solar system which have been studied least with respect to their spectral properties. Of the more than 1,600 presently known asteroids only 15 of the brightest minor planets have been subjected to spectral investigation.

N. T. Bobrovnikov, on the basis of microphotograms of the spectra of 12 minor planets, has established: a) these celestial bodies have no trace of gaseous envelopes and b) the differences in spectral reflectivity of the minor planets are relatively great. In the case of certain asteroids the blue part of the spectrum is very weak; for others the reflection of sunlight is almost neutral. Best of all, investigations were made of the spectral properties of the asteroid Vesta, although completely inadequately. A. N. Deych at Pulkovo obtained a spectrogram of Vesta from which he determined that the violet part of its spectrum actually is attenuated in comparison with the spectra of stars of the sun type. The observations of Bobrovnikov, Johnson and the author apparently indicate periodic changes of the color of Vesta, agreeing with the period of the changes of its brightness determined by Grunewald and Kuiper.

Intensity also decreases in the red part of the spectrum of Vesta (Fig. 6). Colorimetric observations of the minor planets have shown that their color is extremely varied. This fact is of considerable interest for solution of the problem of the origin of asteroids. Spectral observations of the minor planets for the time being confirm colorimetric data and should be continued for the purpose of accumulating information on the reflectivity of asteroids in different parts of the spectrum.

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We have considered briefly only an insignificant part of the results of study of the planets obtained using the spectral method of investigation. In planetary astronomy there are many more problems whose solution is possible only with the aid of spectral observations. In the near future our country will have powerful telescopes equipped with spectral apparatus. Observations with these instruments will result in considerable advancement of our knowledge concerning physical conditions on the planets. Particularly broad possibilities will be afforded investigators of the planets by the establishment of astronomical observatories on the moon and artificial earth satellites. Carried beyond the limits of the earth's atmosphere, telescopes and spectrographs will make it possible to detect in the atmospheres of other planets even small quantities of those gases whose presence on the planets of the solar system for the time being remains hypothetical.

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PLANETARY SPECTRA